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Stratigraphy and Chronology of Raised Marine Terraces, Bay View Ridge, Skagit County, Washington

Robert T. Siegfried
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STRATIGRAPHY AND CHRONOLOGY OF RAISED MARINE TERRACES,
BAY VIEW RIDGE,
SKAGIT COUNTY, WASHINGTON


by
Robert T. Siegfried


Accepted in Partial Completion
of the Requirements for the Degree
Master of Science





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ABSTRACT

The evidence presented suggests that terraces and related features found on Bay View Ridge, Skagit County, Washington are raised marine in origin, and formed 13,000 - 11,000 years before present during the Everson Interstade of the Fraser Glaciation. Methods of investigation included topographic profiling, geologic mapping of surface deposits, identifying primary sedimentary structures, grain-size distribution analyses, identifying textural surface features on quartz grains utilizing the Scanning Electron Microscope and radiocarbon age dating.

Little or no measurable differential vertical tectonic and/or glacio-isostatic relative movement has occurred at Bay View Ridge since the Everson Interstade. Volcanic ash found in two peat bogs on Bay View Ridge is believed to have resulted from the eruptions of Mount Mazama.

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INTRODUCTION

Bay View Ridge is an upland located on the Skagit Delta, between the Skagit and Samish Rivers (Fig. 1). It is comprised of glacial sediments that were deposited during the Fraser Glaciation. This topographic feature is semi-linear trending northwest-southeast, three kilometers west of Burlington. Padilla Bay forms the western boundary. Bay View Ridge encompasses an area of approximately thirty-one square kilometers, and reaches a maximum elevation of sixty-seven meters.

GEOLOGIC SETTING

Bay View Ridge lies in the north central Puget Lowland, an elongate structural and topographic trough that has been modified by Pleistocene deposition and erosion. It is bounded by Vancouver Island and the Olympic Mountains on the west, and the Cascade Range on the east. Most of the lowland lies below one hundred fifty meters. The western lowland consists of elongate waterways, believed to have originated from glacial erosion of the last major glaciation cutting into its own proglacial outwash plain (Crandell and others, 1965; Easterbrook, 1969). The eastern lowland consists of broad post-glacial alluvial valleys and deltas fed by streams and rivers emanating from the Cascade Range.

Four major continental glaciations are believed to have entered the lowland; the Orting, Stuck, Salmon Springs, and Fraser Glaciations (Crandell and others, 1958; Easterbrook, 1976). This thesis is concerned with the positions of relative sea level at Bay View Ridge following the Vashon Stade of the Fraser Glaciation.

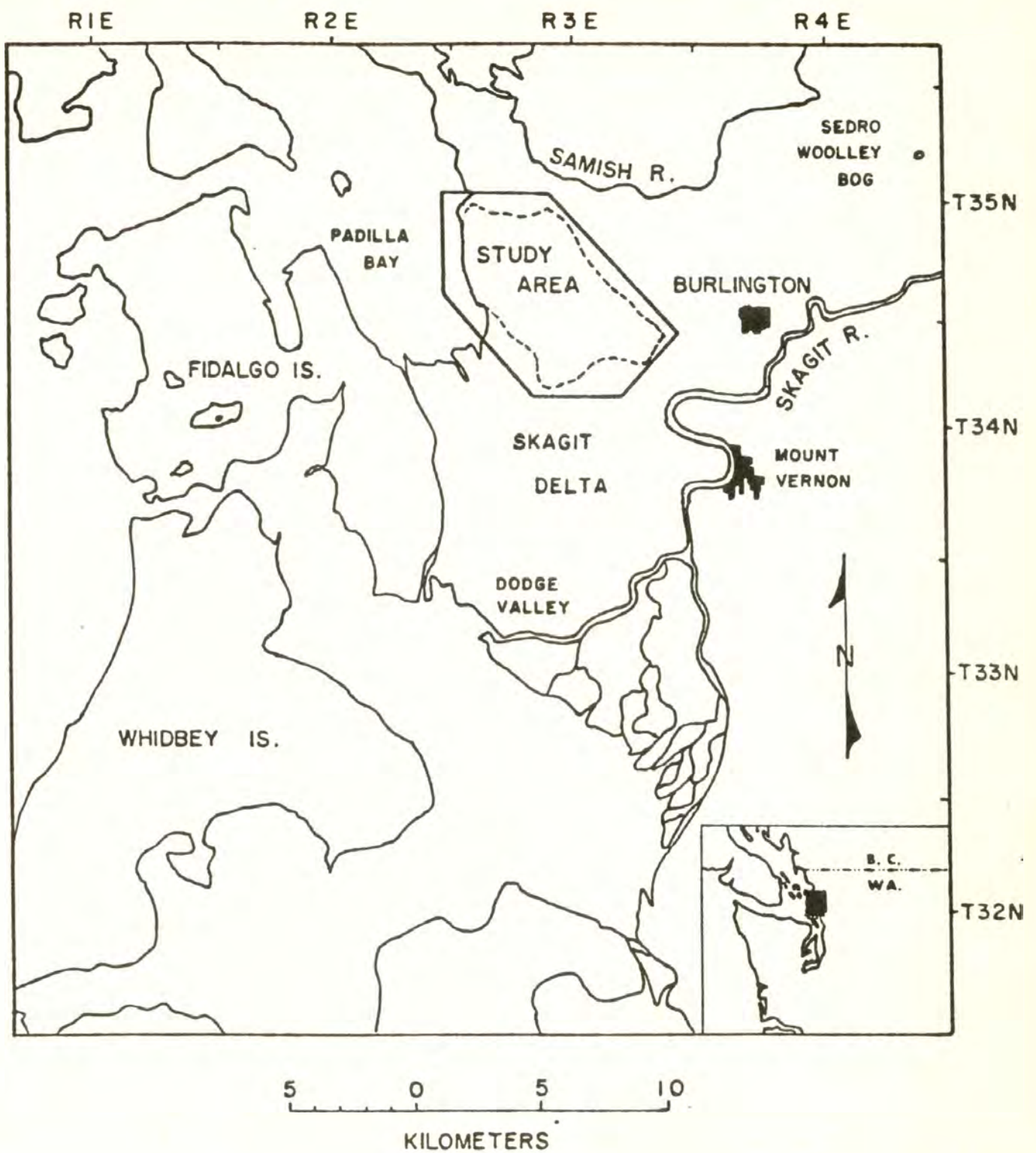


Figure 1. Location map

PREVIOUS INVESTIGATIONS

J Harlin Bretz (1913) presented evidence concerning the changes in relative positions of sea level in the northern Puget Lowland. Bretz inferred upper limits of relative sea levels at twelve meters at Mount Vernon and seven and one-half meters at Cattle Point Hill on San Juan Island. These elevations were determined from the lowest occurrences of Vashon recessional outwash. Evidence for higher sea levels was reported in various locations in the San Juan Islands. These included fossiliferous marsh sediments at eighty-two meters, along with sediments described as marine clays bearing shell fragments at eighty-eight meters on Orcas Island. Other evidence supporting post-glacial marine submergence of the San Juan Islands included terracing at Cattle Point Hill and South Hill on San Juan Island.

"Distinct benches are preserved in sod-bound gravels on the southern face of Cattle Point Hill, the two highest being 240 feet and 175 feet. South Hill has a similar bench at 265 feet, but none below." (Bretz, 1913).

In Whatcom County, Bretz described a deltaic-like deposit derived from a heavily loaded stream flowing through the Squalicum Channel near Bellingham. He determined that relative sea level was perhaps fifteen meters above present during Vashon recession.

Sceva (1950) reported that Vashon recessional outwash was deposited in a lake or marine embayment that occupied the Skagit River basin. He stated the following:

"The surface of the lake was 150 feet or more above the present sea level. These deltaic deposits of sand and gravel are well exposed in gravel pits near Butlers Camp in the northern part of Sec. 17, T. 35 N., R. 4 E. The delta is believed to have extended entirely across the present Skagit Valley". (Sceva, 1950).

Sceva went on to say:

"While the coarse-grained materials were being deposited in the delta, fine-grained materials were settling off shore. Beds of fine clay that may be a part of this deposit are exposed on top of glacial till on Bay View Ridge." (Sceva, 1950).

Well log data revealed that fifty feet of this clay was penetrated before till was encountered. I believe that this clay is Everson glaciomarine drift (discussed later).

Easterbrook (1963) presented information concerning relative sea level for Whatcom County. Elevations for late Pleistocene relative sea level in northern Whatcom County are presented in Figure 2. He explains that submergent conditions prevailed after Vashon recession. This was followed by one short period of emergence, one of resubmergence, and finally a re-emergence. The submergent episodes were recorded by the deposition of glaciomarine drift, where glacial debris, melted from floating berg or shelf ice, engulfed underlying marine organisms. The glaciomarine deposits are named the Kulshan glaciomarine drift and the Bellingham glaciomarine drift, respectively. The intervening emergence is represented by a fluvial deposit, the Deming sand. This sequence marks the Everson Interstade of the Fraser Glaciation in Whatcom County and southwestern British Columbia (Armstrong and others, 1965). Deposits of the Deming sand are absent south of Bellingham Bay. Consequently deposits of glaciomarine drift to the south are designated under one name, the Everson glaciomarine drift (Easterbrook, 1968, 1969). Radiocarbon dates bracket the Everson Interstade at between about 13,000 - 11,000 years B.P. (Easterbrook, 1966).

Radiocarbon dates	Rock stratigraphic units	Relative sea level
	Recent alluvium	As present
11,950 \pm 180, marine terrace; 9,920 \pm 760, limiting peat date	Sumas outwash outwash sand and gravel; silt, silt, clay, and peat; marine terrace deposits	About 12-24 meters higher than present; may have been lower during late stage of deposition
11,700 \pm 150 to 11,400 \pm 170	Sumas drift till and ice-contact deposits; gravel and sand	
11,800 \pm 400 12,090 \pm 350 10,370 \pm 300	Bellingham glaciomarine drift pebbly clay till-like drift; pebbly clay; contains marine fossils	150-210 meters higher than present
11,640 \pm 270	Deming sand sand; interbeds of clay, silt gravel and peat	about 12-18 meters higher than present
11,660 \pm 350 12,970 \pm 280	Kulshan glaciomarine drift pebbly clay till-like drift; pebbly clay; contains marine fossils	about 90 meters higher than present
Younger than about 24,000 years B.P.	Vashon till till; minor lenses of sand and gravel	

Figure 2. Post Vashon geochronology and relative sea level for Whatcom County, Washington. Adapted from Easterbrook, 1963, 1966; and Armstrong, 1977.

Radiocarbon dates delimiting the age of Everson glaciomarine drift range from 10,370 \pm 300 to 13,010 \pm 170 years B.P. Easterbrook, 1969.

Emergent conditions again prevailed after deposition of Bellingham glaciomarine drift, approximately ten to eleven thousand years B.P. (before present, 1950). The Sumas Stade of the Fraser Glaciation is represented by subaerial Sumas drift overlying Bellingham glaciomarine drift. Datable materials from Sumas drift have been dated by Armstrong and range from $11,700 \pm 150$ to $11,400 \pm 170$ years B.P. (Armstrong, 1977). Basal peat from bogs formed in kettles and abandoned melt water channels, indicate minimum ages for Sumas outwash at $9,920 \pm 760$ (Pangborn bog) and $9,300 \pm 250$ (Fazon Lake) years B.P. (Easterbrook, 1966). Easterbrook (1966) reported a radiocarbon date of $11,950 \pm 180$ years B.P. from marine shells found in sands from a twelve meter terrace at Fish Point on Lummi Peninsula. He believes that the terrace formation occurred in late Bellingham time or possibly early Sumas time (Easterbrook, personal communication).

Easterbrook attributes the possible causes of these rapid changes in relative sea level to two opposed tendencies; isostatic uplift of the land due to glacial unloading, and the eustatic rise in sea level superimposed on tectonic subsidence.

Relative sea level is believed to have been about one hundred twenty meters higher than present, 12,500 years B.P. in the vicinity of the San Juan Islands (Easterbrook, 1969).

Schwartz and others (1972) reported submerged terraces at seven and nine meters in Birch Bay. Biederman (1967) and Mathews and others (1970) present evidence suggesting that throughout most of the Holocene, sea level changes in the vicinity of the Puget Lowland were primarily eustatic.

Basal peat from a peat bog near Sedro Woolley (elevation one hundred five meters) (Rigg, 1958), sixteen kilometers east of Bay View Ridge, was radiocarbon dated at $12,900 \pm 330$ years B.P. (Rubin and Alexander, 1958). This implies that terrestrial conditions have persisted above that elevation to the present (Mathews and others, 1970).

Seven kilometers northeast of Bay View Ridge, Easterbrook (1966) demonstrated that outwash terraces (elevation thirty meters) along the Samish River near Butler Flat are post-Everson in age. The terraces both truncate and are banked up against the slightly older Everson glaciomarine drift. These terraces of possible Sumas origin are graded to a relative sea level of some elevation below the present terrace surface.

Vashon recessional outwash was mapped by Wunder (1976) on the flanks of Pleasant Ridge, near Dodge Valley nine kilometers south of Bay View Ridge. The deposit reaches an elevation of approximately fifteen meters, and contains many large marine bivalves. A shell from the deposit has recently been dated at $11,330 \pm 70$ years B.P. (Robinson, personal communication). The date implies a Sumas-Everson time of origin for the deposit.

Artim and Wunder (1976) mapped a portion of Bay View Ridge as primarily Vashon till, with occasional ice-contact drift. Groups of strandlines that appear on Bay View Ridge were attributed to either ice marginal activity or of the influence of littoral processes.

PURPOSE OF INVESTIGATION

The first objective of this investigation was to determine if terrace forms and related features found at Bay View Ridge are attributable to littoral processes. The geographic and topographic proximity of Bay View

Ridge to the surrounding lowland, along with occurrences of Everson glaciomarine drift, located on Bay View Ridge and near Bay View Ridge, indicate that the area in question was submerged during the Everson Interstade.

After completion of the first objective, a second objective was considered. The second objective was to determine when the raised marine terraces and related features were formed.

Satisfactory completion of the above objectives may provide helpful information to the large scale investigation of post-Vashon eustatic, tectonic and/or isostatic history of the northern Puget Lowland.

BASIS OF SITE SELECTION

Bay View Ridge was chosen primarily because it affords visible terraces at various locations around the ridge. Although exposures do not abound, several excellent exposures are available with respect to terrace forms. Access to areas is uncomplicated. Several roads traverse the area and pastures cover a reasonable extent. The field area is relatively small and has excellent aerial photograph coverage.

METHODS AND OBSERVATIONS

PRELIMINARY INVESTIGATIONS

Topographic Profiles

Three profiles were measured traversing sections of Bay View Ridge (see map; Figs. 3 and 4). One was along Farm-to-Market Road (Highway 237) (A-A') on the northern portion of Bay View Ridge, and another along Wilson Road (B-B'), just east of the community of Bay View. The third profile was along Persons Road (C-C') on the western portion of Bay View Ridge. A transit and a Philadelphia Rod were employed for this purpose. Road intersections served as elevation reference points because of the lack of established benchmarks close by.

Horizontal distances were measured using stadia intervals for longer distances while pacing was satisfactory for shorter distances. Elevation measurements were taken on natural ground adjacent to the roadway. Elevation was measured to one one-hundredth of a foot. The placement of individual stations was determined by changes in the topography.

Results of the three profiles appear in Figures 3 and 4. Similar terrace sequences can be seen at twenty-eight and thirty-four meters in all of the profiles. A prominent terrace at forty-seven meters appears along Farm-to-Market Road and also is shown on the topographic map, just south of Wilson Road (Johnson Road), toward the eastern side of Bay View Ridge (see map). I believe these terraces are marine in origin. Evidence will be presented later. Strandlines that parallel topographic contour lines are also demonstrated to have littoral origins. They connect the measured terraces laterally, and indicate that the terraces, measured at

TOPOGRAPHIC PROFILES

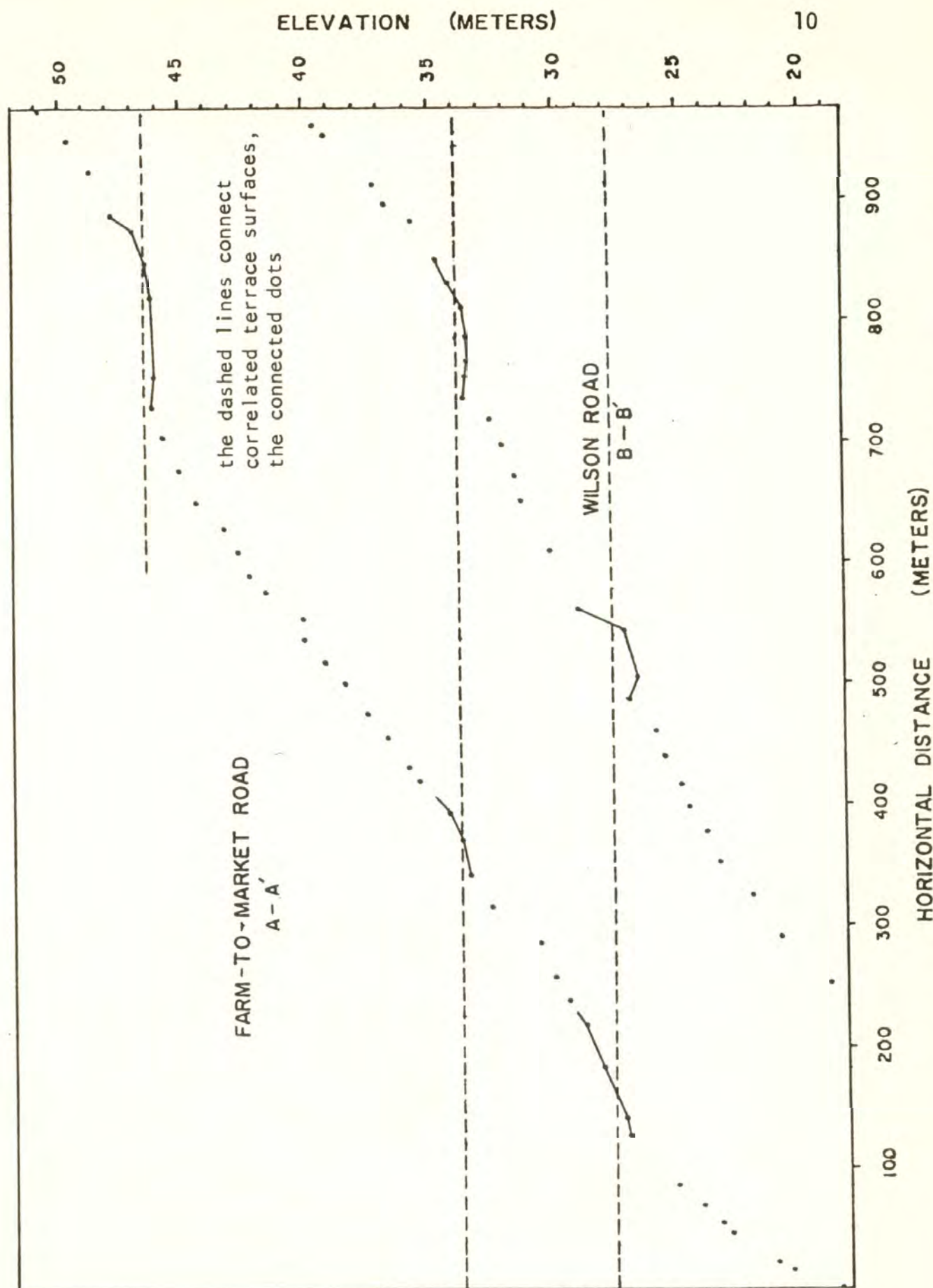


Figure 3. Topographic profiles along Farm-to-Market Road and Wilson Road

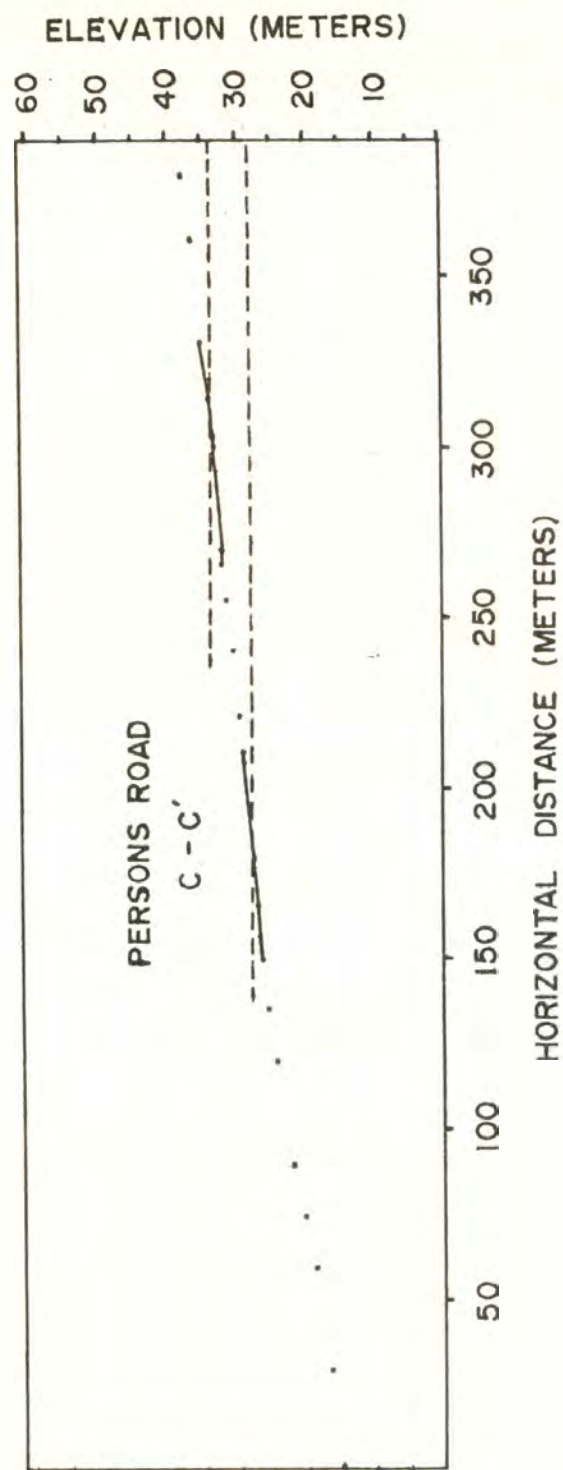


Figure 4. Topographic profile along Persons Road. The dashed lines show that the terrace surfaces along Persons Road compare favorably with the terrace surfaces shown in figure 3.



Figure 5. 28 meter terrace along Wilson Road

different localities, and having equivalent elevations, were formed at the same former sea level.

Surficial Geologic Map

I constructed a geologic map of surface deposits, utilizing aerial photographs, along with available exposures in gravel pits, roadcuts, seacliffs, drainage ditches, and construction sites. Where exposures were not available, such as grassy pasture lands, known contacts were traced laterally at various intervals utilizing a shovel and soil auger. Contacts were inferred where dense vegetation was encountered or augering was impaired by cobbles at depth. Strandlines, seen on aerial photographs, were transferred onto the base map.

EXAMINATION OF DEPOSITS

Pebble Counts on Vashon Till

No datable material was found in the outwash gravels or the till exposed at Bay View Ridge. Most tills exposed at the top of stratigraphic sections in the northern Puget Lowland are Vashon till, however, there are exceptions. Two pebble counts of one hundred pebbles or cobbles were conducted on till from two different locations to determine if the deposits have Canadian lithologies, or were derived from the Washington Cascades. The pebbles and cobbles were taken from the large gravel pit located on the northeastern tip of Bay View Ridge and the small gravel pit on the southern end of Bay View Ridge.

Results of the two pebble counts appear in Table 1. Rocks typical of Canadian provenance include potash-feldspar bearing granites, quartzites,

Table 1. Pebble lithology of Vashon till at Bay View Ridge. Sample A is from the small gravel pit at the southern end of Bay View Ridge. Sample B was taken seven kilometers north of sample A at the northeastern end.

	Sample A	Sample B
K-feldspar-bearing granite	5%	3%
Other granitic rocks	7%	11%
Diorite	5%	2%
Andesite-basalt	31%	43%
Porphyries	8%	6%
Aphanitic volcanic rocks	2%	3%
Breccia	1%	3%
Hornfels	1%	4%
Quartzite	17%	11%
Phyllite		1%
Chert	3%	6%
Conglomerate		2%
Graywacke	3%	1%
Gabbro	3%	1%
Pegmatite		1%
Ultramafic rocks		1%
Assorted metamorphic rocks	14%	1%
	<hr/> 100%	<hr/> 100%

and diorites. A high percentage of andesite-basalt occurred in the samples, but none were of Mount Baker origin. No rocks of recognizable Washington Cascade lithologies occurred in the samples

The stratigraphic sequence in which the till occurs strongly suggests that this is Vashon till. Fluvial sands and gravels of unknown thickness, probably Esperance, are overlain by till. In some locations at Bay View Ridge, a pebbly clay, resembling Everson glaciomarine drift, overlies the till. This stratigraphic sequence, involving Vashon till, is common to the northern Puget Lowland (Easterbrook, 1966, 1969). An excellent typical exposure can be seen in the large borrow pit at the northeastern end of Bay View Ridge.

Pipette Analysis of Everson Glaciomarine Drift

Several outcrops of a till-like deposit overlying till, near or at the surface, are found at Bay View Ridge. The individual units have physical characteristics similar to Everson glaciomarine drift. The material is massive, contains pebbles with some cobbles and occasional boulders, and is less compact than till. It is more argillaceous than till, and exhibits a blocky weathering characteristic upon exposure. The material at Bay View Ridge contains no macrofossils. Samples taken from these units were wet sieved and pipetted for silt and clay content. The sand, silt, and clay percentages were then compared to previously published results from fossiliferous glaciomarine drift (Easterbrook, 1962).

Results of wet sieve and pipette analyses of the pebbly clay appear in Table 2. Particle sizes greater than -1ϕ are not truly represented in the results due to the small sizes of the samples analyzed. They

Table 2. Gravel, sand, silt, and clay ratios from five pebbly clay samples collected at Bay View Ridge

Sample	% < -1 ϕ	% sand	% silt	% clay
1	6.33	22.99	40.14	30.54
2	1.98	12.58	72.78	12.67
3	8.19	37.26	39.13	15.42
4	1.47	16.82	50.35	31.36
5	7.62	24.62	56.71	11.05

probably represent about 10% or less of a bulk sample.

Particle size distributions compare favorably with those published by Easterbrook on Bellingham glaciomarine drift (Easterbrook, 1962).

Silt and clay percentages are somewhat greater than those published by Easterbrook. These deposits are mapped and referred to as Everson glaciomarine drift throughout the remainder of this paper.

Grain-size Distribution Analyses of Sand Samples

A small, shallow gravel pit is located directly west and immediately adjacent to the large borrow pit in the northeastern portion of Bay View Ridge. 1.0-1.5 meters of well sorted and well rounded, stratified, coarse sand and gravel are exposed in the pit. This is underlain by a variable thickness of medium to fine sand. The lower unit contains finely laminated sand that is cross-bedded at low angles with slightly finer, nonlaminated sand.

A survey line was run to this pit, and a benchmark established. The surface boundaries of the pit were then mapped by plane table and allidade. Elevations ranged from forty-four meters at the southern end to thirty meters at the northern end of the pit.

Sand samples were collected from various locations within the pit, and then marked on the map for later interpretation. The samples were taken parallel to bedding, and as thin as possible, to avoid mixing grain populations. The samples were then sieved at half phi intervals. Cumulative percent curves were constructed, and various statistical parameters calculated both graphically and with the aid of a computer. Graphs were plotted to assist in determining depositional environment, utilizing methods

outlined by Friedman (1967).

The formulas employed for the statistical parameters obtained from sieving data appear in Figure 6. Statistical parameters for twelve samples of laminated terrace sands appear in Table 3. Graphs comparing the various parameters appear in Figures 7, 8, 9, and 10. The dashed lines separating beach and river sands were adapted from Friedman (1967). The circled dots represent average values of the parameters for the twelve samples displayed.

The graphs do not present conclusive evidence that the sieved sand samples were deposited in a littoral environment. However, the significance of the graphs will be discussed further in a later section.

Scanning Electron Microscope

The Scanning Electron Microscope (SEM) has allowed researchers to identify minute textural features on the surfaces of quartz grains. Diagnostic features identified from grains taken from present day depositional environments may be utilized in identifying grains taken from ancient deposits. For an up-to-date summary of the current state of the art and included bibliography, see Krinsley and Doornkamp (1973).

Several samples of the laminated sands described in the previous section were collected for the purpose of SEM viewing. The samples were prepared and mounted in the manner outlined by Krinsley and Doornkamp (1973). The specimens were viewed with an AMR 1200 scanning electron microscope.

Approximately forty quartz grains collected from three laminated sand samples from the northeastern sand and gravel pits on Bay View Ridge were viewed utilizing the scanning electron microscope. Micrographs of surface textures that were representative of the grains viewed appear

Statistical Measure	Symbol	Formula
Mean	(\bar{x})	$1/100 \sum fm$
Standard Deviation	(σ)	$(\sum f(m_{\phi} - \bar{x}_{\phi})^2 / 100)^{1/2}$
Mean Cubed Deviation	$(\alpha 3\sigma^3)$	$1/100 \sum f(m_{\phi} - \bar{x}_{\phi})^3$
Inclusive Graphic Standard Deviation	(σ_I)	$\frac{\phi_{84} - \phi_{16}}{4} + \frac{\phi_{95} - \phi_5}{6.6}$
Inclusive Graphic Skewness	(SK_I)	$\frac{\phi_{16} + \phi_{84} - 2\phi_{50}}{2(\phi_{84} - \phi_{16})} + \frac{\phi_5 + \phi_{95} - 2\phi_{50}}{2(\phi_{95} - \phi_5)}$

Figure 6. Moment formulas from Friedman (1967); Inclusive Graphic formulas Folk (1974)

Table 3. Statistical parameters for sieve data

Sample	(\bar{x})	(σ)	$(\sigma)^3$	$(\alpha_3 \sigma^3)$	(σ_I)	(SK_I)
1	2.176	0.631	0.251	0.115	0.58	0.095
2	1.925	0.816	0.543	0.178	0.75	0.147
3	1.927	0.643	0.266	-0.029	0.56	0.084
4	2.594	0.605	0.228	0.018	0.53	0.000
5	2.247	0.523	0.143	-0.042	0.44	0.077
6	2.153	0.588	0.203	-0.048	0.48	-0.102
7	2.255	0.567	0.183	0.025	0.52	0.028
8	2.094	0.595	0.211	0.089	0.55	0.128
9	2.351	0.645	0.268	0.089	0.65	-0.038
10	2.321	0.615	0.232	0.213	0.56	0.240
11	2.754	0.690	0.328	0.065	0.68	0.056
12	2.184	0.589	0.204	0.106	0.52	0.094

4.25 ϕ for the < 62 μ fraction

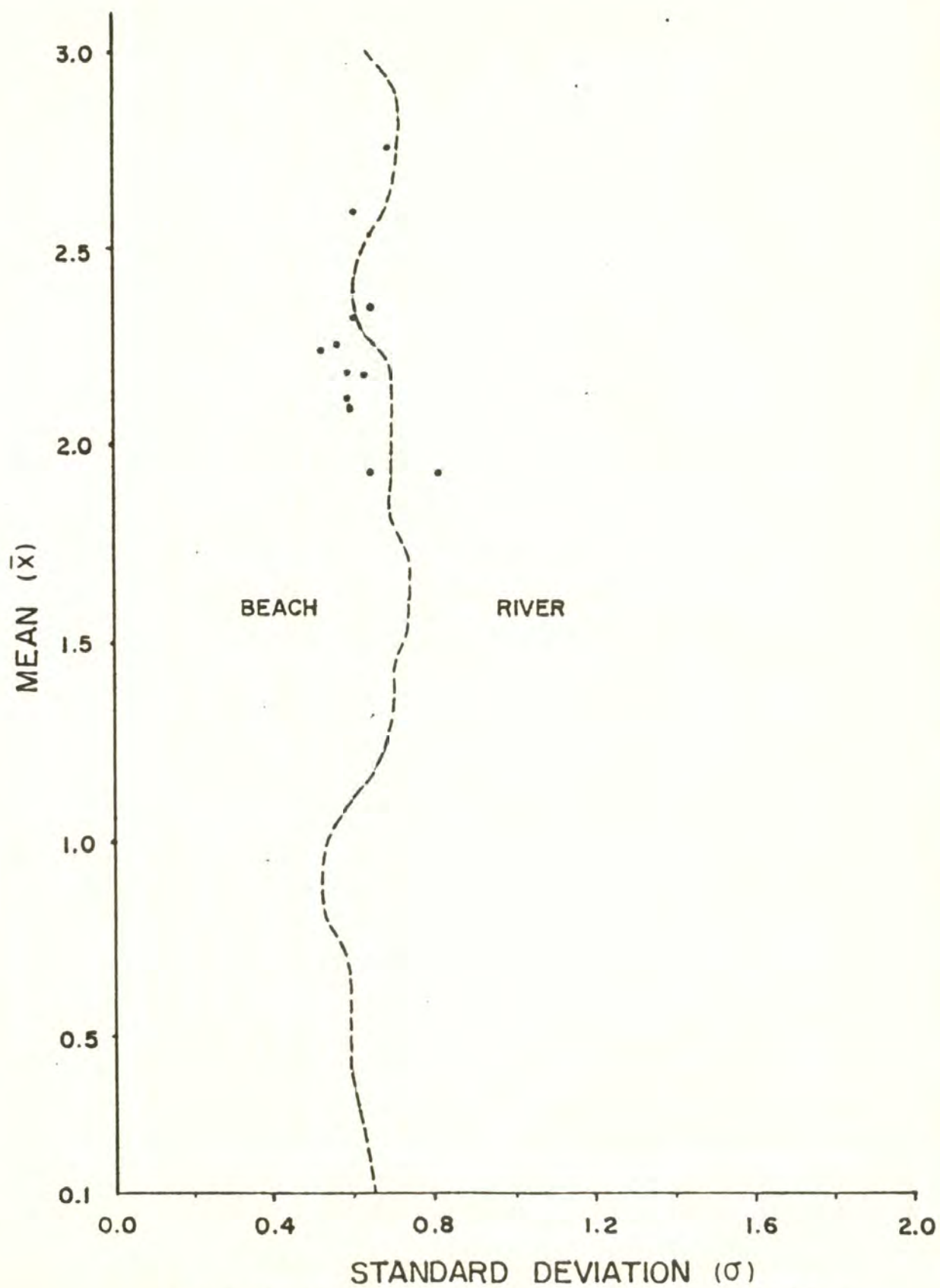


Figure 7. Mean particle size vs. standard deviation

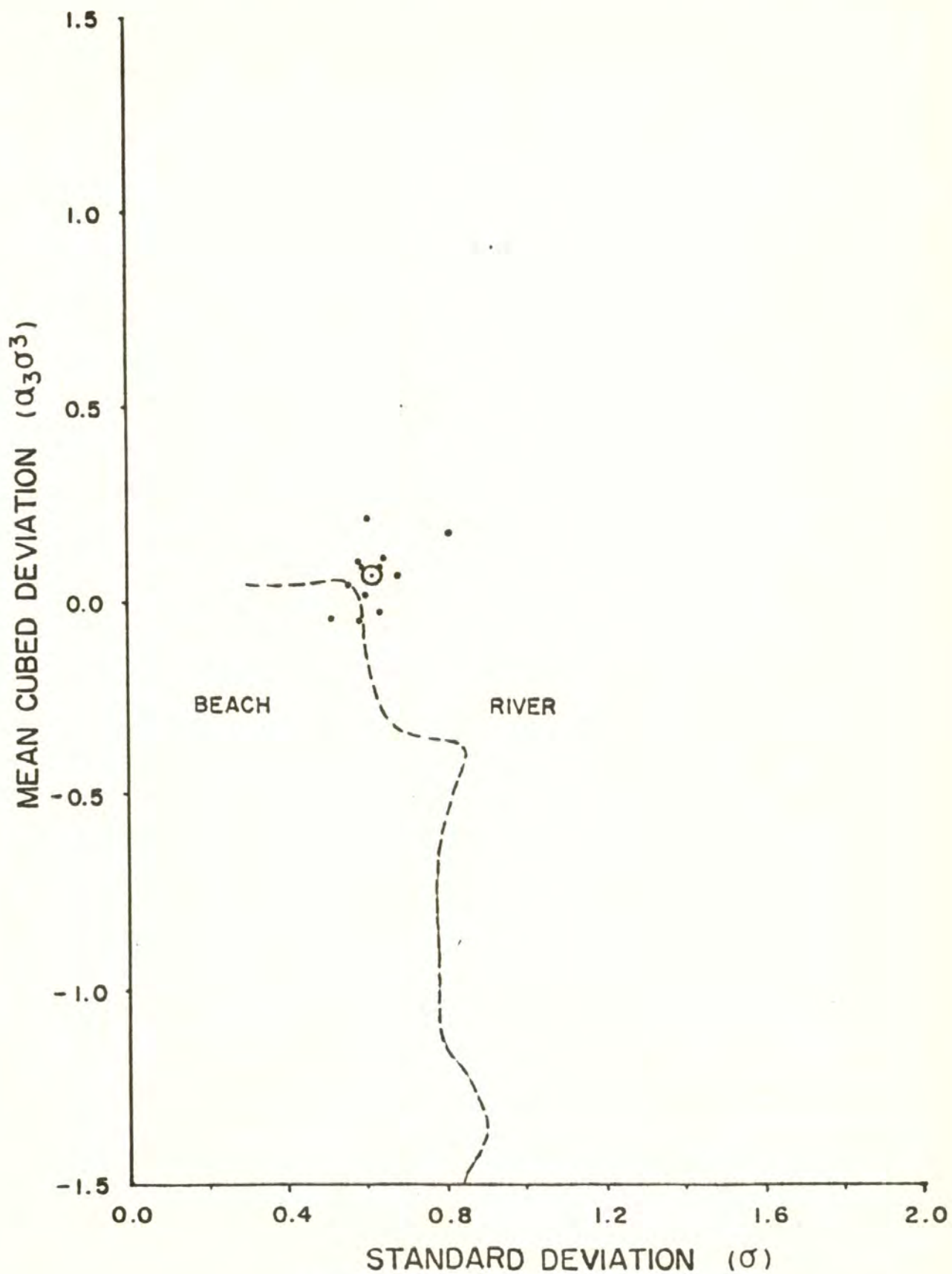
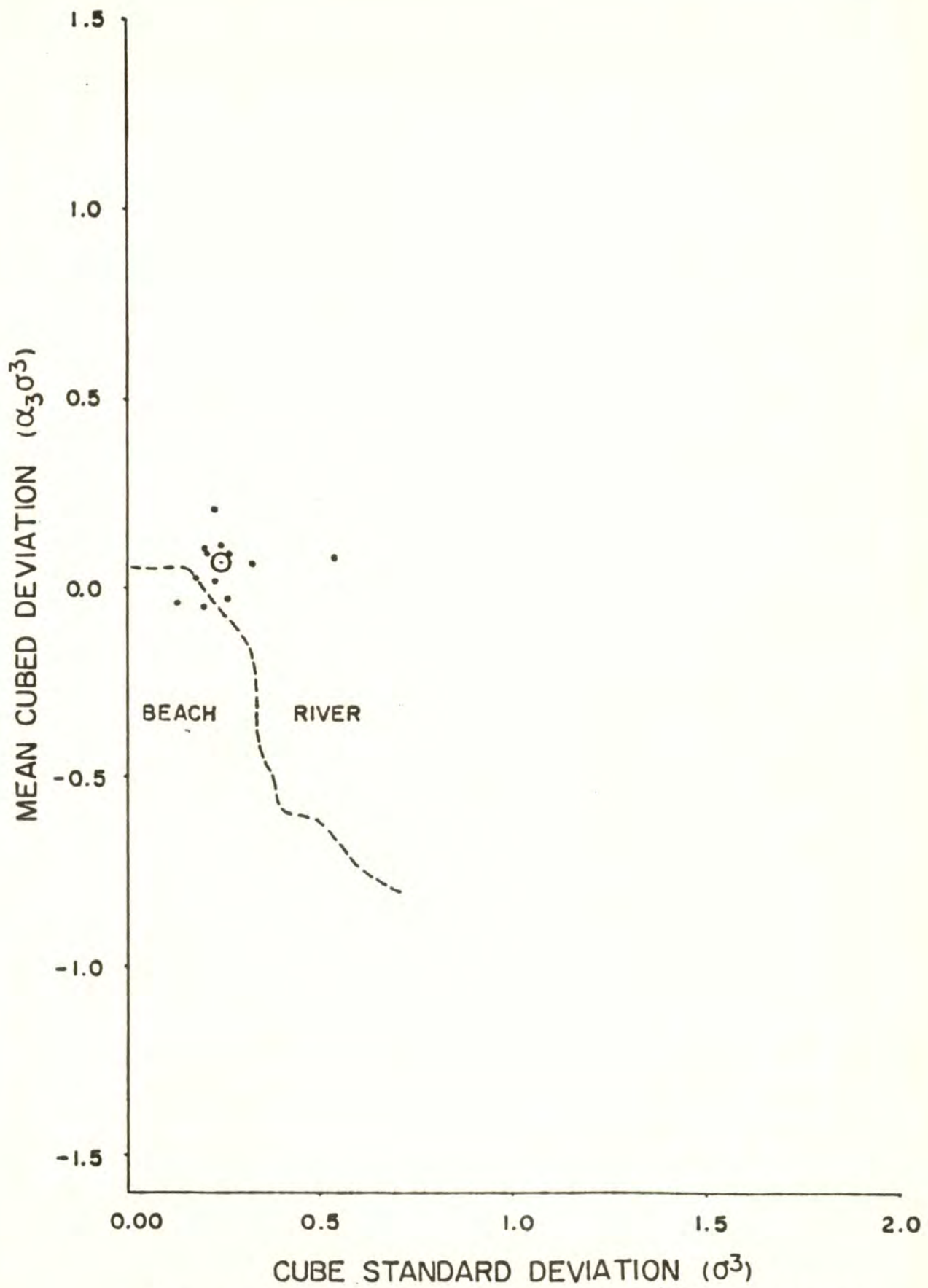


Figure 8. Standard deviation vs. mean cubed deviation



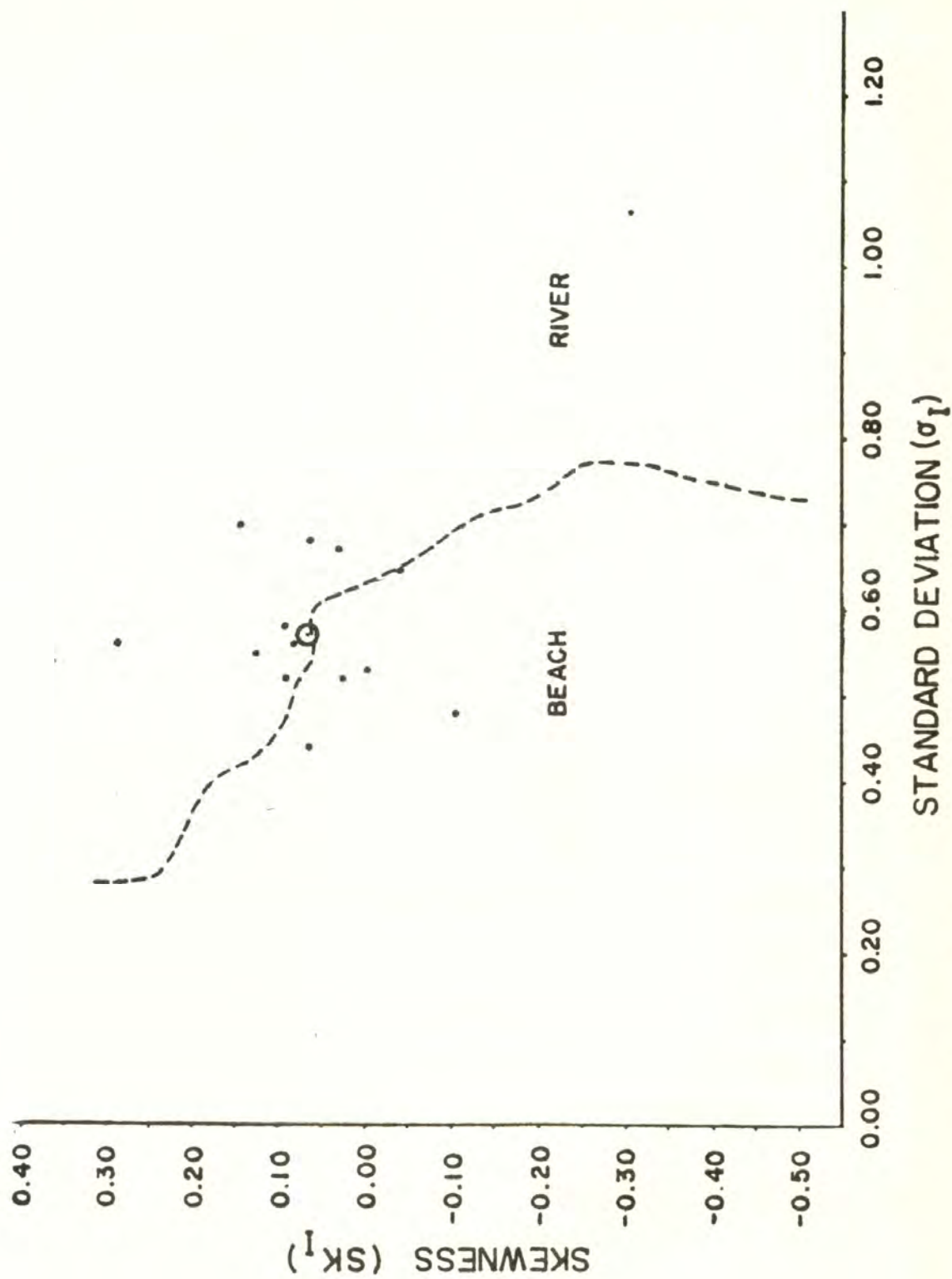


Figure 10. Inclusive standard deviation vs. inclusive graphic skewness

in Figures 11, 12, 13, and 14. The identified features found on respective grains are displayed in the figures. Many of the features identified are diagnostic of glacial and subaqueous impact (littoral) environments.

Radiocarbon Chronology

No datable material was located in direct association with any of the terrace deposits on Bay View Ridge. This prevented any direct dating of these deposits, consequently, the absolute ages and elevations of former relative sea levels could not be determined. Subaerially deposited peat was located for radiocarbon dating purposes. The radiometric age of basal peat establishes minimum dates for relative sea levels at Bay View Ridge.

Three shallow peat bogs were located on Bay View Ridge (see map). Their elevations are fifty-eight meters (bog #2), forty-seven meters (bog #3), and forty meters (bog #1) respectively. The two higher bogs were cored with a Hiller peat corer, while the lower bog was cored with a soil auger. A basal peat sample was collected from the fifty-eight meter bog one hundred ninety centimeters from the surface. Another basal peat sample, two hundred ten centimeters below the surface, was obtained from the forty-seven meter bog. This bog had the distinct odor of hydrogen sulfide. Both bogs were underlain by a meter or less of alternating layers of bluish-gray, silty sand and clay. This in turn was underlain by a bluish-gray silty clay of unknown thickness.

A basal peat sample collected seventy-five centimeters below the surface was taken from the forty meter bog. This bog was underlain by bluish-gray silty clay of unknown thickness.

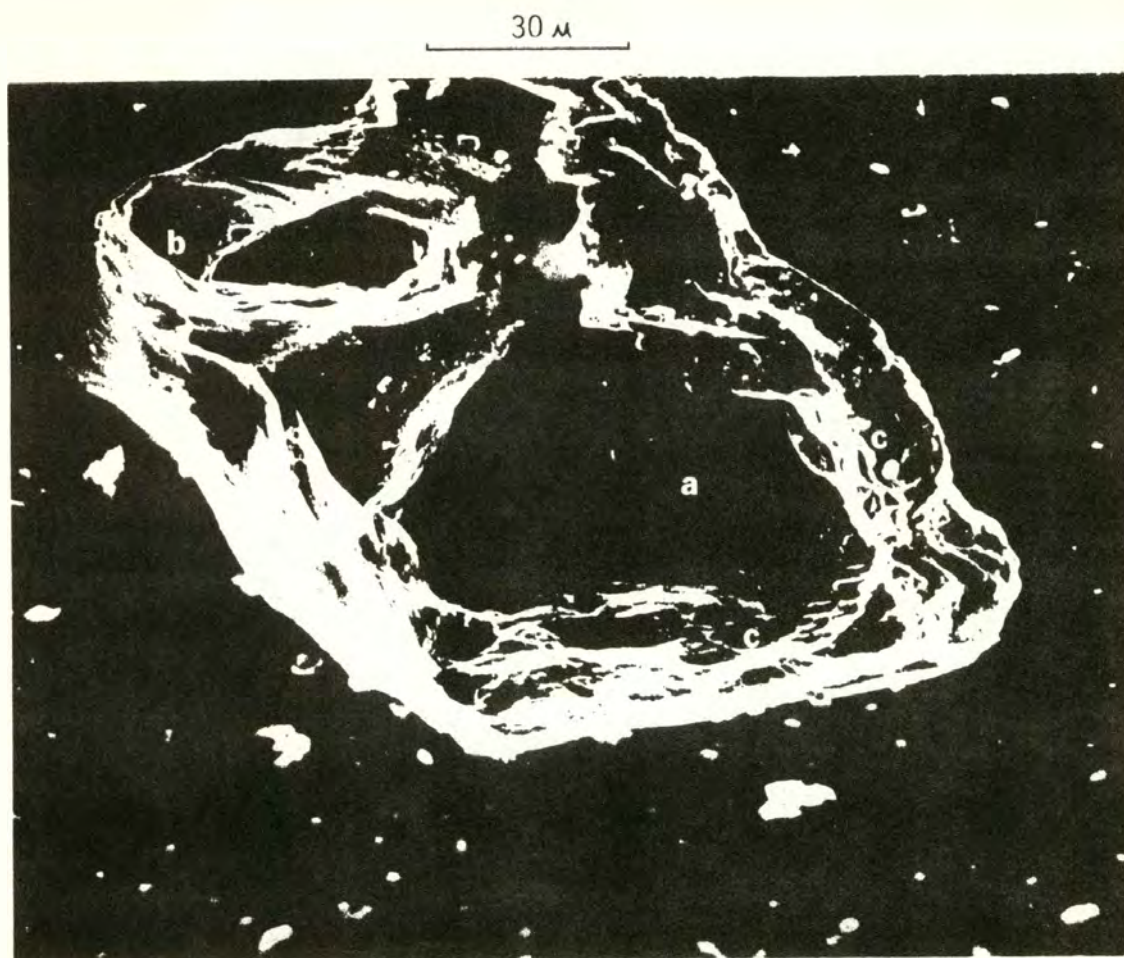


Figure 11. Quartz grain showing conchoidal fracture, flatness, and high relief characteristic of grains transported by a glacier.

- a. Flat cleavage face; darker areas represent mechanical breakage
- b. Conchoidal fracture
- c. Mechanically upturned plates; white areas represent silica precipitation

All SEM prints by Walter Robinson



Figure 12. Grain showing glacial, littoral, diagenetic features.

- a. Conchoidal fracture pattern nearly destroyed by solution and reprecipitation rounding
- b. Mechanically upturned plates; large and small V-shaped impact marks on the upturned plates are probably due to subaqueous (littoral) impact
- c. Slightly curved groove with possible satellite V's nearly destroyed by solution and reprecipitation



Figure 13. Grain showing possible chemically etched oriented V's and abundant solution and reprecipitation

- a. Chemically etched oriented V's diagnostic of low energy littoral environments
- b. Upturned plates accentuated by solution and reprecipitation

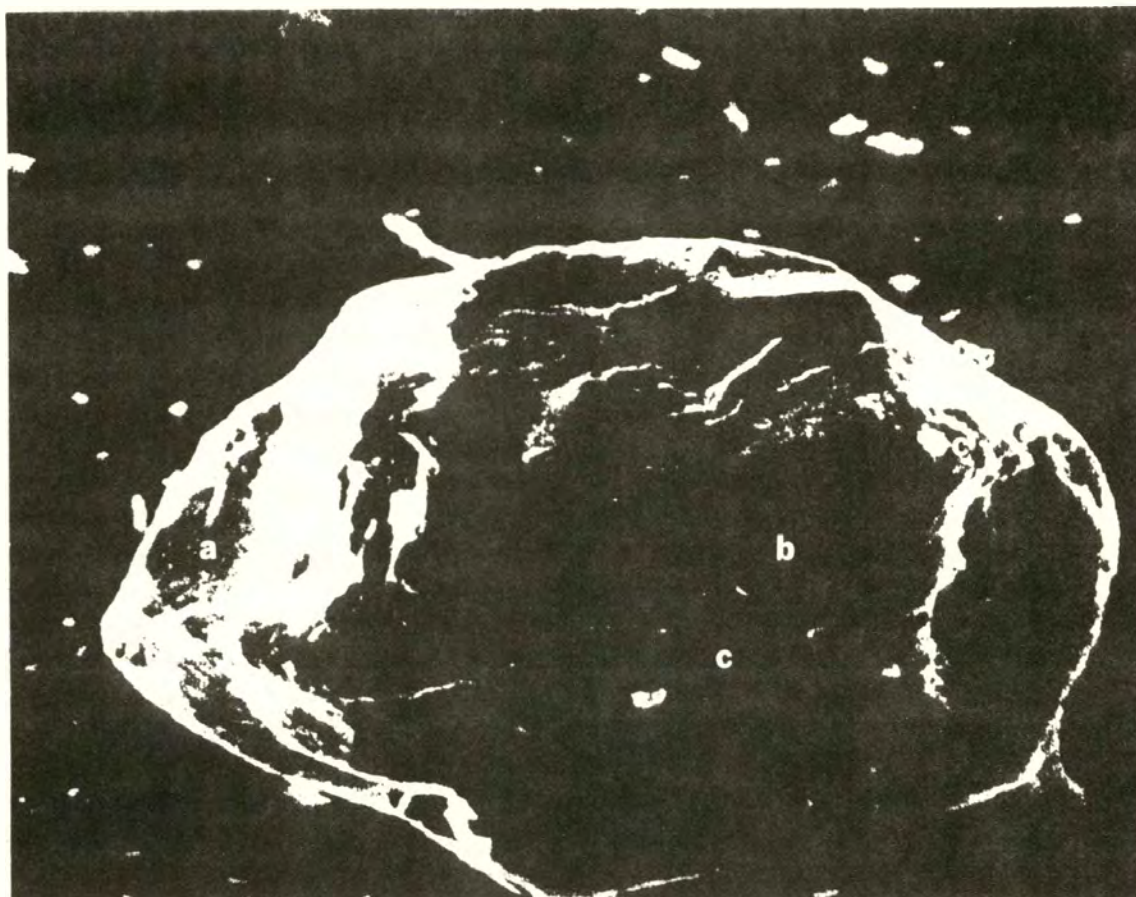
30 μ 

Figure 14. Grain showing conchoidal fracture smoothed and rounded by precipitation in a littoral environment.

- a. Conchoidal fracture smoothed and rounded by solution and precipitation
- b. V forms (mechanical or chemically etched?)
- c. Upturned plates accentuated by solution and precipitation

The peat from the three bogs was decomposed and contained small amounts of silt and clay. Several thin layers of diatomite were present in the peat.

The peat samples were collected and prepared in the manner outlined by Stuiver (Othberg and Ferguson, 1977), and dated by the U. S. Geological Survey radiocarbon laboratory in Menlo Park, California.

A yellow volcanic ash (2-5 cm thick) at a depth of one hundred twenty centimeters below the surface was encountered in the two upper bogs. Most of the ash found under such circumstances in the northern Puget Lowland is probably Mazama Ash (Easterbrook, personal communication).

Radiocarbon dates from the three basal peat samples collected appear below. The samples were dated by Stephen W. Robinson, U. S. Geological Survey Radiocarbon Dating Laboratory, Menlo Park, California.

<u>Bog</u>	<u>Radiocarbon years before present (1950)</u>	<u>Lab No.</u>
58 m	8,200 \pm ?	(USGS 341)
47 m	11,700 \pm 110	(USGS 342)
40 m	2,180 \pm 50	(USGS 340)

DISCUSSION

Fraser Deposits

The Vashon Stade of the Fraser Glaciation appears to be well represented in the sediments at Bay View Ridge. The early portion of Vashon ice advance is represented by cross-bedded, pebbly sand grading upwards to cross-bedded gravel with scour and fill structures. No dates are available to confirm the time of deposition, but physical characteristics are quite similar to the Esperance Sand Member described by Mullineaux and others (1965) in the Seattle area, and Easterbrook (1969) in the San Juan Islands. A radiocarbon age of $18,000 \pm 400$ years B.P. (I-2282) was obtained from peat associated with the Esperance sand at Marrowstone Head, just east of Port Townsend (Easterbrook, 1969). The Esperance sand is interpreted to have been deposited south of the glacier terminus by streams from the advancing and ablating Vashon ice. Dates ranging from 20,000 years in southwestern British Columbia to 15,000 years near Seattle indicate the time-transgressive nature of the deposit (Easterbrook, 1969). The occurrence of outwash sands grading upwards to gravel at Bay View Ridge would also suggest transgression. The gravel was deposited much closer to the glacier terminus, and was deposited over the earlier deposited sands.

The outwash sand and gravel are overlain by compact and bluish-gray till consisting of a poorly sorted mixture of pebbles, cobbles, sand, silt, clay, and boulders, and containing rocks of Canadian lithologies. The till is thought to be Vashon till. Most of the pebbles are rounded, but some are faceted, polished, and striated. The till is generally in sharp

contact with the underlying gravel, and is interpreted as lodgment till. At some localities at Bay View Ridge the till thins out and becomes slightly better sorted and less compact. The contact with the underlying gravels becomes less apparent, and I interpret the deposit to be ablation till.

The pebbly clay, described earlier, is thought to be Everson glacio-marine drift (Fig. 15). The fifty feet of clay, described by Sceva (1950), is also thought to represent glaciomarine drift.

No sediments of the Sumas Stade of the Fraser Glaciation are found at Bay View Ridge.

Terrace Deposits

Stratified Coarse Sand and Gravel

Coarse sand and gravel cover much of the northern and northeastern portion of Bay View Ridge (see Qbg on map insert). The gravel is well sorted and rounded, and stratified with well sorted coarse sand. In some localities the gravel grades into cobble size material at the contact with the underlying laminated, medium-grained sand (Fig. 16). Excellent exposures of this unit can be seen in the small gravel pit adjacent to the large borrow pit.

This stratified sand and gravel is interpreted to be a beach deposit. The deposits are linear in extent and parallel to contour lines. Any connection with ice-marginal glacio-fluvial activity or ice-contact deposition is ruled out because slump structures, abrupt and extreme changes in grain size, or scour and fill structures, features diagnostic of ice-contact and glacio-fluvial deposition, are nowhere present in



Figure 15. Vashon till in foreground overlain by Everson glaciomarine drift.



Figure 16. Interbedded coarse sand and gravel grading to cobbles, overlying laminated medium grain sand. Note the sharp contact between the cobbles and underlying sand.

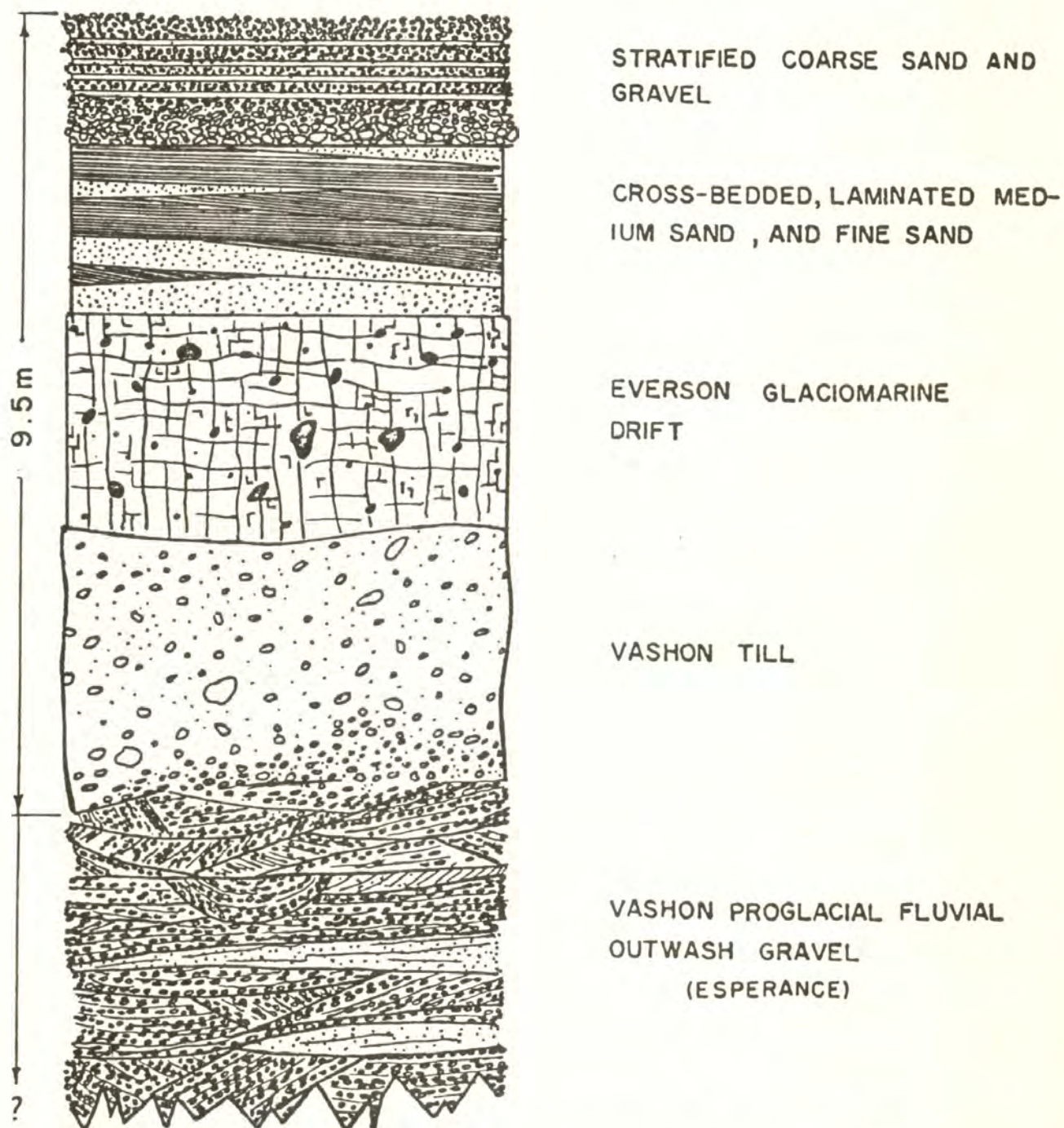


Figure 17. Diagrammatic stratigraphic section representing the Fraser Glaciation as exposed in the northeastern borrow pit at Bay View Ridge. The outwash gravel grades down to predominantly sand. Approximately 30 meters of the Esperance sand is exposed here. The total thickness is unknown at this locality.

the deposits. Veritabily, the stratification in these deposits at Bay View Ridge are characterized by subtle changes in the relative sizes of coarse sand and gravel, and the stratification parallels the gentle slope of Bay View Ridge. Other fluvial activity can be positively ruled out because there is no evidence indicating the presence of former streams traversing Bay View Ridge and no source for the fluvial material exists. Two small intermittent streams cut into Bay View Ridge, and may have transported some of the material to the beach in the past. The primary sources for these deposits are thought to be the underlying Fraser drift.

Cross-bedded and Laminated Medium Sand and Fine Sand

The cross-bedded laminar sand (Fig. 18) at Bay View Ridge is moderately well sorted, containing medium to fine sand. Small amounts of iron oxide staining are present on the individual grains. The cross-beds dip ten degrees or less (Fig. 19). This is typical of beach profiles described by Reineck and Singh (1973).

Friedman (1967) demonstrated that a combination of textural parameters can be applied in the separation of beach swash and backwash sand from river sand. The separation is related to the depositional processes inherent in the two environments, and to the ability of fine and coarse grained material to be deposited or removed from the tail fractions of particle distribution curves. Friedman (1967) concluded that mean particle size is not as environmentally sensitive as standard deviation and skewness. Figure 7 shows that most of the samples sieved fall into the beach category.

Figures 8, 9, and 10 compare skewness calculations against sorting calculations. Although these values plot on either side of the beach-



Figure 18. Raised beach sand and gravel overlying Everson glaciomarine drift.



Figure 19. Interbedded coarse sand, gravel, and cobbles overlying laminated cross-bedded sand and interfingering fine sand.

river boundary, many show positive skewness, which is suggested to be diagnostic of river sand or dune sand (Mason and Folk, 1958; Friedman, 1961, 1967; Chappell, 1967).

The samples tend to plot in Friedman's river category because of the high less than sixty-two micron particle size fraction measured in the samples. This tends to increase the values of all the grain-size parameters calculated, pushing points upwards and to the right on the graphs presented. Are these high silt values attributable to typical fluvial processes, or can they be satisfactorily explained as atypical beach sediments due to abnormal influxes of silt (during or post depositional) that alter normal grain-size distribution?

There are several means by which increased silt content can result:

1. Sediment source rock contains abundant silt (Andrews and Van der Lingen, 1968).
 2. High silt and clay content carried in suspension from glacial outwash.
 3. Insufficient wave energy to remove fines from the swash-backwash zone due to ephemeral increases in sediment load (Friedman, 1967).
 4. Offshore winds blowing fines onto the beach from adjacent dunes (Shepard and Young, 1961; Friedman, 1961; Chappell, 1967).
 5. Diagenetic alteration affecting grain-size distribution due to limonite staining of Pleistocene sand (Chappell, 1967).
 6. Overlying silt percolating into sand deposits after deposition.
- All of the above could have been present in the study area.
1. The sand analyzed is underlain by either glaciomarine drift or till, which is presumed to be the main source of the sand.

Everson glaciomarine drift contains abundant silt and clay-sized particles (Table 2), as does Vashon till.

2. Silt and clay from the outwash channels flowing out the Samish River valley may have reached Bay View Ridge.
3. The amount of silt and clay supplied from the two preceding points may have exceeded the ability of wave energy to selectively remove the fine-grained particles as suggested by Friedman (1967). Equilibrium conditions may have never been attained, resulting in abnormally high silt content.
4. Prevailing winds, at present, are from the southeast in the study area (Keuler, 1978). If these wind conditions prevailed in the past, the sample area would have been subjected to offshore winds. If fine material (of possible dune origin) was blown from the backshore to the foreshore, it may have resulted in higher silt contents in some of the samples collected.
5. Small amounts of iron oxide staining are present on the sand grains of the collected samples. This may have had some influence on measured grain-size distributions as suggested by Chappell (1967).
6. At many localities on Bay View Ridge, reddish-brown silt (believed to be wind blown) overlies the terrace deposits. This silt can be seen occupying the spaces between pebble clasts. It is not known whether these silts are present in the underlying sand.

Several of the samples displayed in Figures 8, 9, and 10 plot within Friedman's beach category and most of the others are near the beach-river boundary. If any of the six points presented above did influence the grain-size distributions at Bay View Ridge, then the negatively skewed

samples that did plot into the beach category may suggest that all the samples were deposited in a littoral environment as was suggested by Chappell (1967) for Pleistocene beach sand from New Zealand that were altered by limonite staining, yet were still negatively skewed. However, the data presented in Figures 7, 8, 9, and 10 remains inconclusive as to whether the sands were deposited in a littoral environment.

Sedimentary structures (cross-bedding and laminations) found in the sand at Bay View Ridge are characteristic of beach profiles. SEM micrographs (discussed later) of surface textural features on sand grains from the deposit suggest that the sand is littoral. The grain-size distribution data displayed in this thesis suggests that environmental interpretation should be based on more than one sample from a given deposit. It also emphasizes that grain-size distribution analysis is not conclusive and diagnostic evidence when interpreting depositional environment of Pleistocene beach sediments in glaciated areas, unless new boundaries can be developed that clearly separate calculated littoral and fluvial statistical comparisons for glaciated areas.

The sand (Fig. 19) that interfingers with the laminated medium sand is fine grained and contains considerable amounts of less than sixty-two micron particles, up to 20% in some samples sieved. Miller and Zeigler (1964) suggested that finer sand grains move slightly shoreward, but are carried back to the breaker zone by backwash. The less than sixty-two micron fraction moves from the breaker zone, and is transported in a seaward direction. Mason and Folk (1958) also noted that the fines are washed shoreward. Bird (1969) reports that stratified layers of finer and coarser sediment within a beach represent alternations of stronger and

The laminated medium sand and interfingering fine sand at Bay View Ridge is interpreted to represent foreshore beach and nearshore facies systems. No environmentally significant changes laterally could be determined for the sample area on the basis of particle size distribution. E.C.F. Bird upon seeing the described sequence at Bay View Ridge stated that he believed it represented a beach sequence.

Scanning Electron Microscope

Features identified on quartz grains include conchoidal breakage features, smoothing and rounding by solution and precipitation, upturned plates (with evidence of both mechanical breakage and solution and precipitation), V-shaped impact marks, some chemical etching, along with other solution and precipitation features (Figs 11, 12, 13, and 14). Conchoidal breakage features on quartz grains are believed to result from glacial grinding and abrasion during glacial transport (Krinsley and Donahue, 1968). However, alternative origins for such features have been suggested (Setlow and Karpovich, 1972; Brown, 1973). The close proximity of glacial sediments to the samples viewed from Bay View Ridge suggest that a glacial origin is the most probable for these grains.

Mechanical breakage features and V-shaped impact marks on quartz grain surfaces are characteristic of deposition in littoral environments (Krinsley and Donahue, 1968; Krinsley and Doornkamp, 1973). Solution features have been found to be characteristic of low energy littoral environments (Margolis, 1968; Setlow and Karpovich, 1972). Krinsley and Donahue (1968) have reported that solution and precipitation features are associated with diagenesis.

Glacial sediments are polygenetic. I have found no references in the literature stating that quartz grains can retain textural features inherited from earlier environments of deposition after glacial transport. I am assuming that these features are destroyed during glacial transport.

Quartz grains from fluvial environments have not been observed to have diagnostic textural features (Krinsley and Donahue, 1963). Krinsley and Donahue (1968) concluded that river abrasion is not sufficient to cause breakage patterns.

V-shaped impact marks are not abundant, and poorly developed in the samples viewed in this study. Whether this is the result of post depositional solution and precipitation, altering or destroying the V-shaped impact marks, or that these are features characteristic of low energy wave regimes is uncertain. Regardless, the presence of conchoidal breakage features, V-shaped impact and chemical solution features add credence to the conclusion that the laminated sand at Bay View Ridge was reworked from glacial sediments by wave action and deposited in a littoral environment.

Problem of Gravel Overlying Sand

The stratified coarse sand and gravel overlying laminated beach sand present a problem as to the mechanism which caused the sequence. Schwartz (Schwartz and Grabert, 1973) contends that this can result from normal processes associated with emergence. Sand is deposited on the lower foreshore and later gravel on the backshore overrides the sand as relative sea level lowers.

Bird disagrees, arguing that backwash is not sufficiently strong enough to move the available pebbles and cobbles shoreward (Bird, personal communication). Bird contends that the gravel would have to be transported from further updrift as beach drift, along the shore and over the sand, when a large sediment source was tapped further updrift.

A study in England by Carr (1974) shows that when shingle is introduced into a drift sector, and wave energy flux is high enough, oblique wave approach will cause the largest particles to travel farthest. At Bay View Ridge the largest material in the gravel is at the base (Fig. 16). Carr's study would appear to support Bird's hypothesis.

I offer a third suggestion. The elevations at which this sequence can be seen at Bay View Ridge range from twenty-five to forty-five meters. Possible sources for large supplies of gravel (ice-contact or proglacial outwash deposits) have not been found above approximately twenty-five meters. A resubmergence of sea level of unknown duration and vertical extent may have occurred during the net emergence of Bay View Ridge. Pebbles and cobbles reworked from ice-contact deposits would move laterally from the south (the updrift direction) as beach drift, and be transported northward in the swash-backwash zone. Ice-contact deposits, containing grain-sizes similar to those found in the terrace coarse sand and gravel, are exposed below twenty-five meters (see Q1c on map along Wilson Road [Johnson Road]). If swash is more effective than backwash in moving coarse material as stated by Bird, then the combination of lateral beach drift and rising relative sea level would account for the present location and elevation of the coarse material which overlies the laminated beach sands. The laminated beach sands would have been deposited during relative emergence prior to the alleged resubmergence if the hypothesis is correct. This would not appear to violate the Bruun Rule, where erosion takes place on the landward side of a transgressing sea (Schwartz, 1967), because an erosional contact separates the sand from the gravel and cobbles (Fig. 20).



Figure 20. Erosional contact between laminated cross-bedded sand and terrace gravel and cobbles. The reddish-brown silt between the cobble and gravel clasts is believed to be wind blown. Penny for scale in lower middle right.

Relation Between Strandlines, Terraces, and Uplift

Strandlines in many localities can be seen superimposed on areas mapped as beach terrace deposits (Qbg) (see map). A tight group of strandlines can be seen trending toward the large borrow pit (that exposes the littoral deposits) on the northeastern end of Bay View Ridge at about forty-five meters. This demonstrates that the origin of the strandlines and terraces is related to littoral processes, and not ice-marginal activity as proposed by Artim and Wunder (1976) as one possibility for their origin.

Strandlines are also found on areas not mapped as terrace deposits. Many of these that intersect drainage ditches along roadsides contain slight increases in gravel content, but in others a change is not readily apparent. These occurrences were too small to appear at the map scale used.

As explained earlier, strandlines parallel topographic contour lines at Bay View Ridge. Strandlines can be seen at various elevations as can terrace forms. For the most part, strandlines seem to group at the same elevations as surveyed terraces. Groups of strandlines were connected with terraces and extrapolated around Bay View Ridge. This demonstrates that little or no vertical differential uplift has occurred at Bay View Ridge since relative sea level lowered.

Chronology from Peat Bogs

Assuming no contamination, the radiocarbon dates from basal peat samples indicate the beginning of accumulation at the respective bog sites on Bay View Ridge. The dates span a broad time period (11,700-2,180

R.C. years B.P.). The two bogs (Nos. 2 and 3; see map) containing volcanic ash had basal peat dated at 11,700 and 8,200 years B.P. The dates suggest that the ash found in these two bogs is Mazama ash, which was deposited approximately 6,600 years ago (Wilcox, 1965). This is further supported when accumulation rates are calculated in years per centimeter, and constant deposition is assumed:

58 meter bog	47 meter bog
$\frac{8200 \text{ yrs.}}{190 \text{ cm}} \cdot 120 \text{ cm} = 5179 \text{ yrs.}$	$\frac{11,700 \text{ yrs.}}{210 \text{ cm}} \cdot 120 \text{ cm} = 6686 \text{ yrs.}$

While these calculations are by no means definitive, they do suggest that the ash found in these bogs may have resulted from the eruptions of Mount Mazama.

Relative Sea Level and Geochronology

If the pebbly clay found at Bay View Ridge is Everson glaciomarine drift, marine waters covered the study area during the Everson Interstade. Most of the dates obtained from Everson glaciomarine drift in the north-central lowland range from 13,000 - 12,000 years B.P. (Easterbrook, 1966). The highest occurrence of this material identified at Bay View Ridge was found at forty-nine meters at the northeastern borrow pit. Terrace gravels range from the highest point on Bay View Ridge (67 meters (220 ft.)) to near present day sea level (see map insert).

Horizontal strandlines of littoral origin superimposed on these deposits allow extrapolation around Bay View Ridge correlating the forty-seven meter terrace with the forty-seven meter bog. The terrace indicates a stillstand in relative sea level at forty-seven meters. Whether or not this occurred 11,700 years B.P. cannot be determined. The bog date

does indicate that relative sea level could not have exceeded forty-seven meters 11,700 years B.P., providing the date is correct. The date fits in chronological order between the dates from the Sedro Woolley bog (12,900 years B.P., 105 m) and Dodge Valley (11,330 years B.P., 15 m).

Mathews and others (1970) have implied that glacio-isostatic rebound was essentially completed by about eight thousand years before present. Biederman (1967) and Mathews and others (1970) have presented evidence suggesting that relative sea level was very near present day sea level by about five thousand years before present in the northern Puget Lowland. No evidence supporting or disputing this was found at Bay View Ridge.

CONCLUSIONS

1. The terraces at Bay View Ridge are raised marine terraces. Terrace deposits and related deposits are of littoral origin. This is confirmed by primary sedimentary structures, sorting and rounding characteristics in gravels, and identified surface textural features on quartz grains.
2. The designated beach category of Friedman (1967), determined from grain-size distribution analyses, may not be conclusive and diagnostic for identifying Pleistocene littoral sand that was deposited in glaciated areas.
3. Marine terraces at twenty-eight meters, thirty-four meters, and forty-seven meters are correlated around Bay View Ridge. The terrace correlations, along with horizontal strandlines of littoral origin, indicate that little if any relative differential tectonic and/or glacio-isostatic vertical uplift has occurred at Bay View Ridge after the Everson Interstade.
4. Relative sea level stood at or below forty-seven meters $11,700 \pm 110$ years before present at Bay View Ridge.
5. Volcanic ash found in two peat bogs on Bay View Ridge probably resulted from the eruptions of Mount Mazama.

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